Bi-Sat Observations of the Lunar Environment Above Swirls (BOLAS):

Tethered Microsat Investigation of Space Weathering and the Water Cycle at the Moon

Tim Stubbs, Michael Collier, Bill Farrell, John Keller, Jared Espley,
Michael Mesarch, Dean Chai, Michael Choi, Richard Vondrak,
Michael Purucker (*GSFC*), Ben Malphrus, Aaron Zucherman (*Morehead State U.*),
Robert Hoyt (*Tethers Unlimited*), Michael Tsay (*Busek*), Jasper Halekas (*U. Iowa*),
Tom Johnson (*Wallops*), Pam Clark (*JPL*), Georgiana Kramer (*PSI*),
Dave Glenar, Jacob Gruesbeck, (*U. Maryland*)

Planetary Science Deep Space SmallSat Studies (PSDS3)

BOLAS Science Targets and Rationale

The overarching science goal of the BOLAS mission is to determine the role of the solar wind in space weathering and the creation of water products on the surface of the Moon by investigating crustal magnetic fields and the swirl patterns that typically accompany them.

Primary science:

- **Space weathering** – regolith exposure to solar wind protons
- **Lunar water cycle** – role of solar wind in forming OH/water
- **Solar wind interaction with crustal fields**

Secondary science:

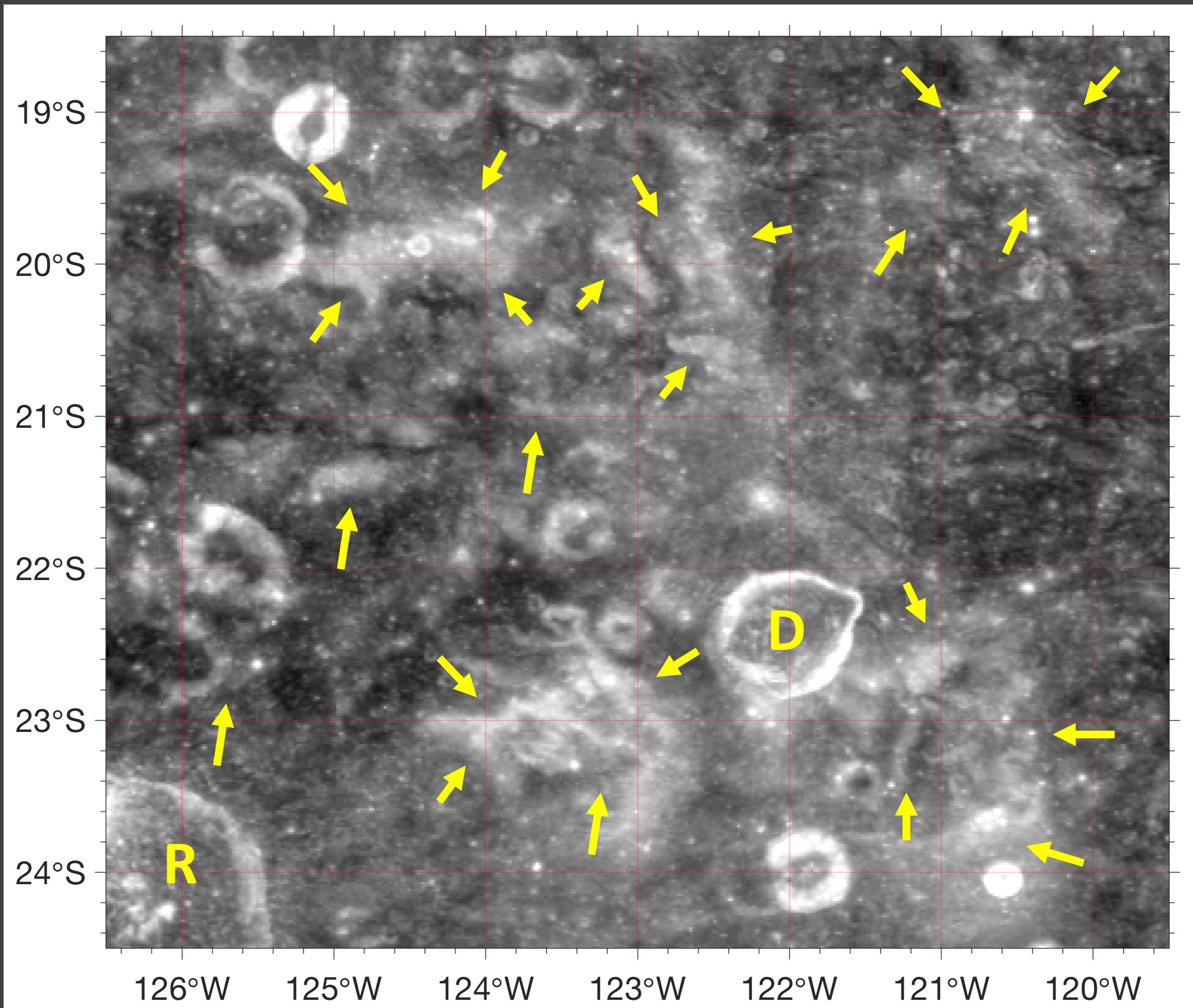
- **Crustal magnetism**
- **Effect of impacts on regional magnetism**
- **Moon's global interaction with the solar wind**
- **Exospheric dust transport**
- **Lunar ionosphere**

Primary target:

Gerasimovich – amongst strongest crustal magnetic fields with extensive swirl patterns. Located on farside around 21°S, 123.5°W

BOLAS Science – Swirls, Space Weathering and Water

WAC Reflectance (643 nm)

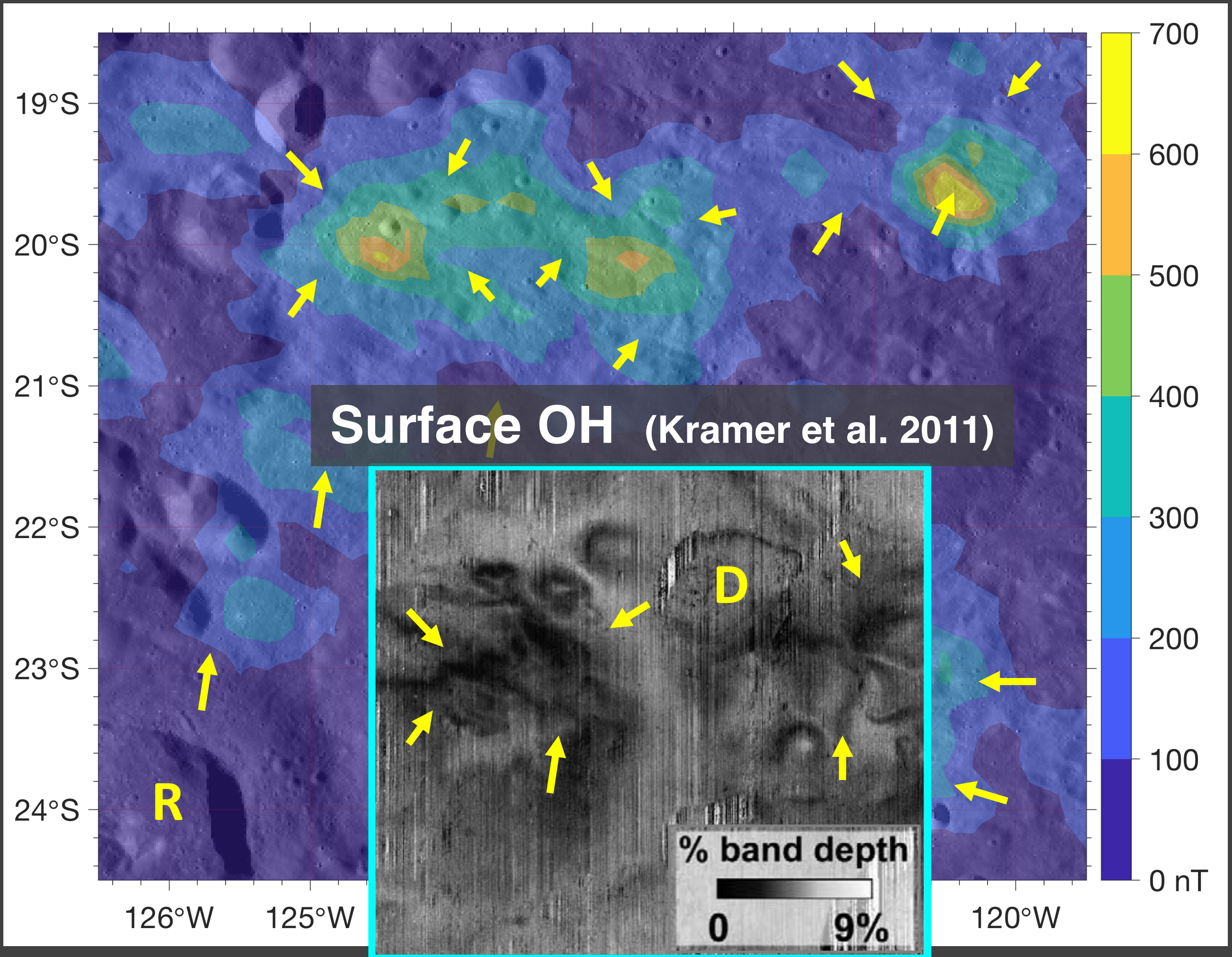


Gerasimovich

visibly bright "pristine" swirl patterns

BOLAS Science – Swirls, Space Weathering and Water

Surface Magnetic Field [nT] (Tsunakawa et al. 2015)



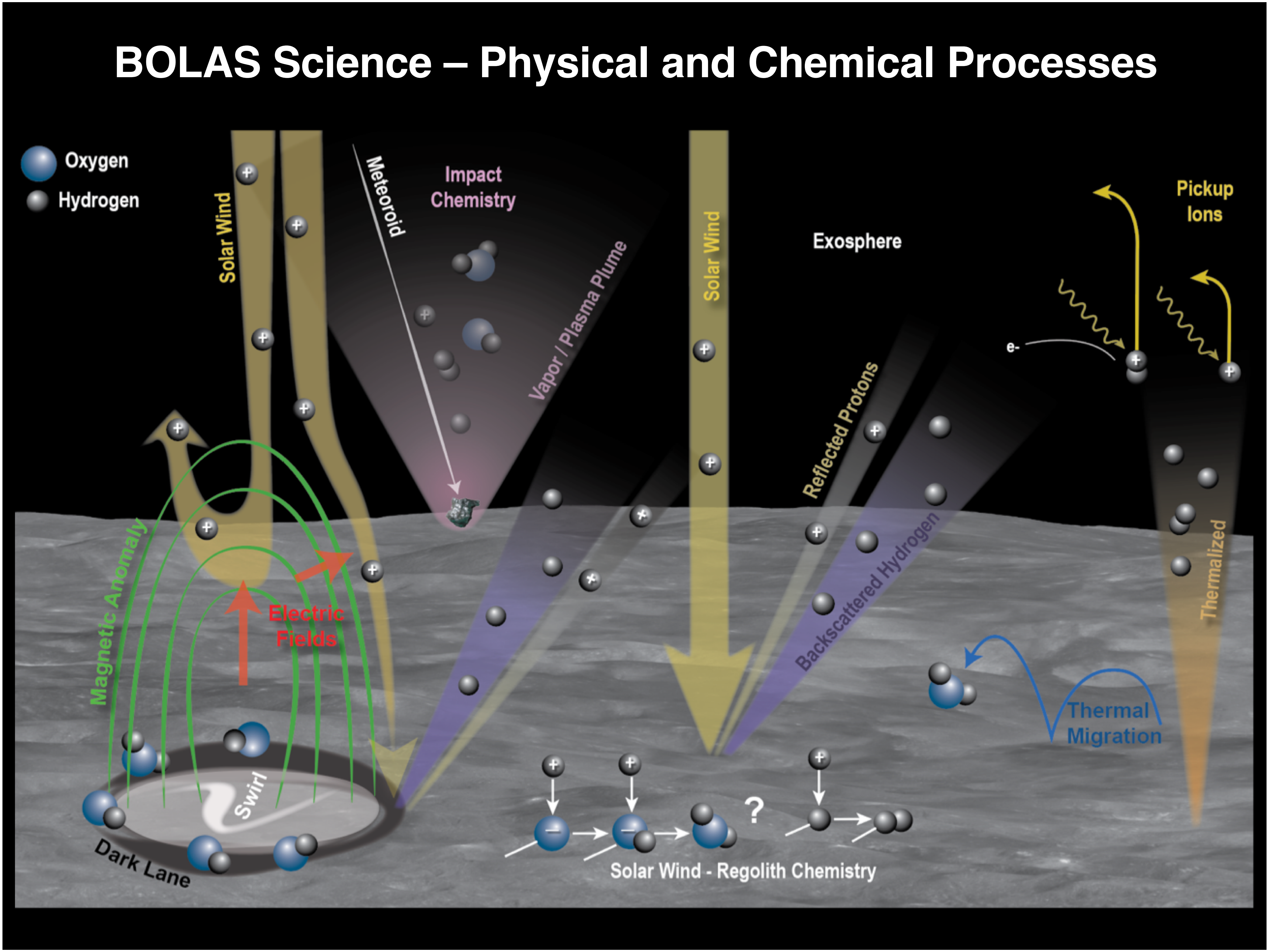
Gerasimovich

visibly bright "pristine" swirl patterns

coincide with strong crustal magnetic fields

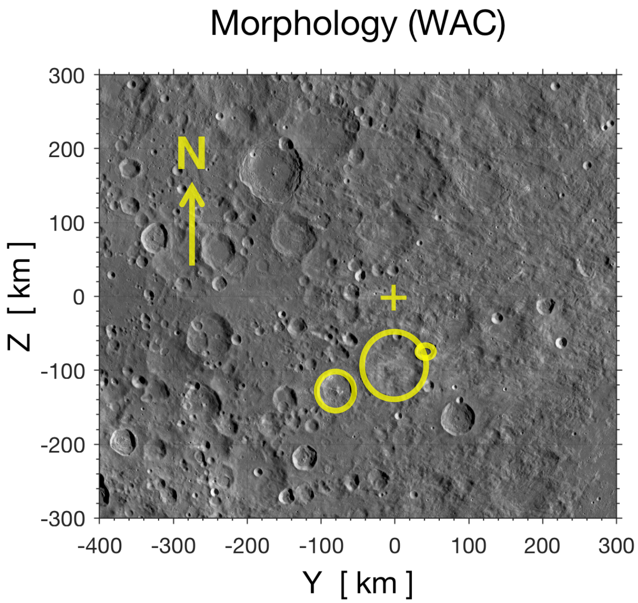
coincide with absence of OH

indicates that crustal fields shield surface regolith from space weathering and OH formation by the solar wind


BOLAS Science – Physical and Chemical Processes
Oxygen
Hydrogen
Solar Wind
Meteoroid
Impact Chemistry
Vapor / Plasma Plume
Solar Wind
Exosphere
Pickup Ions
e-
Reflected Protons
Backscattered Hydrogen
Thermalized
Magnetic Anomaly
Electric Fields
Swirl
Dark Lane
Thermal Migration
?
Solar Wind - Regolith Chemistry

BOLAS Science – 3D Hybrid Simulation of Gerasimovich

SURFACE

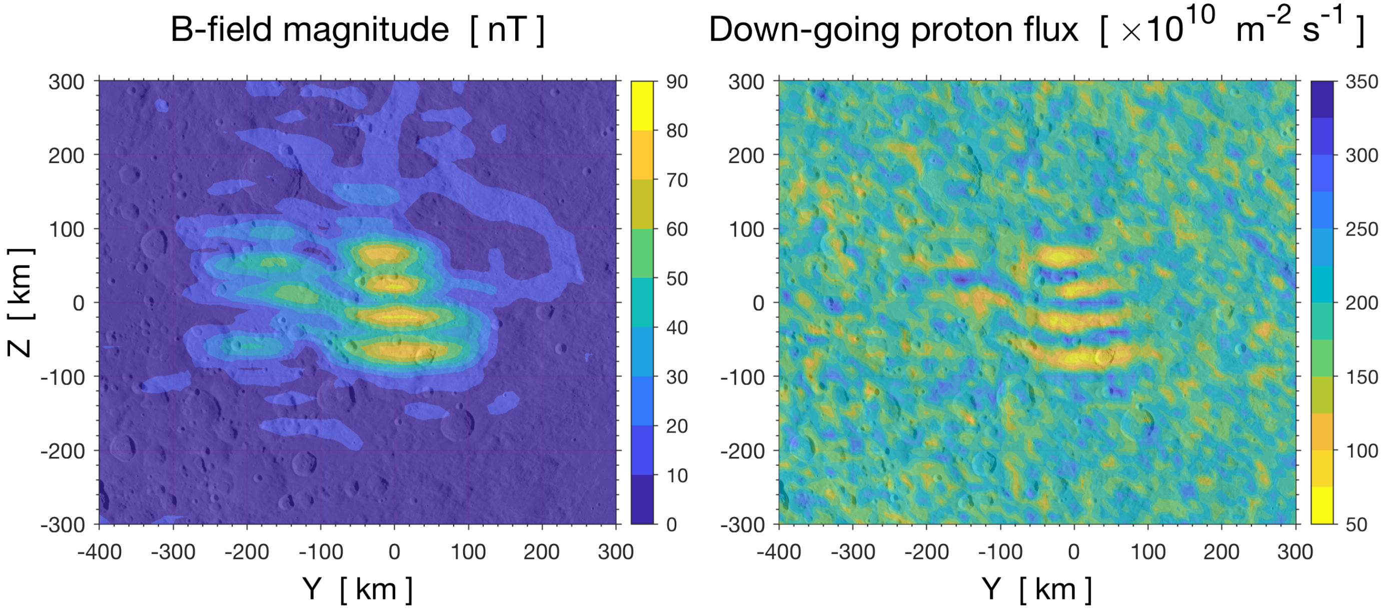


Results from 3D self-consistent hybrid code (Fatemi et al., 2015)

- **Uses realistic crustal field (Purucker and Nicholas, 2010)**
- **10 × 10 km resolution at the surface (Y – Z plane)**

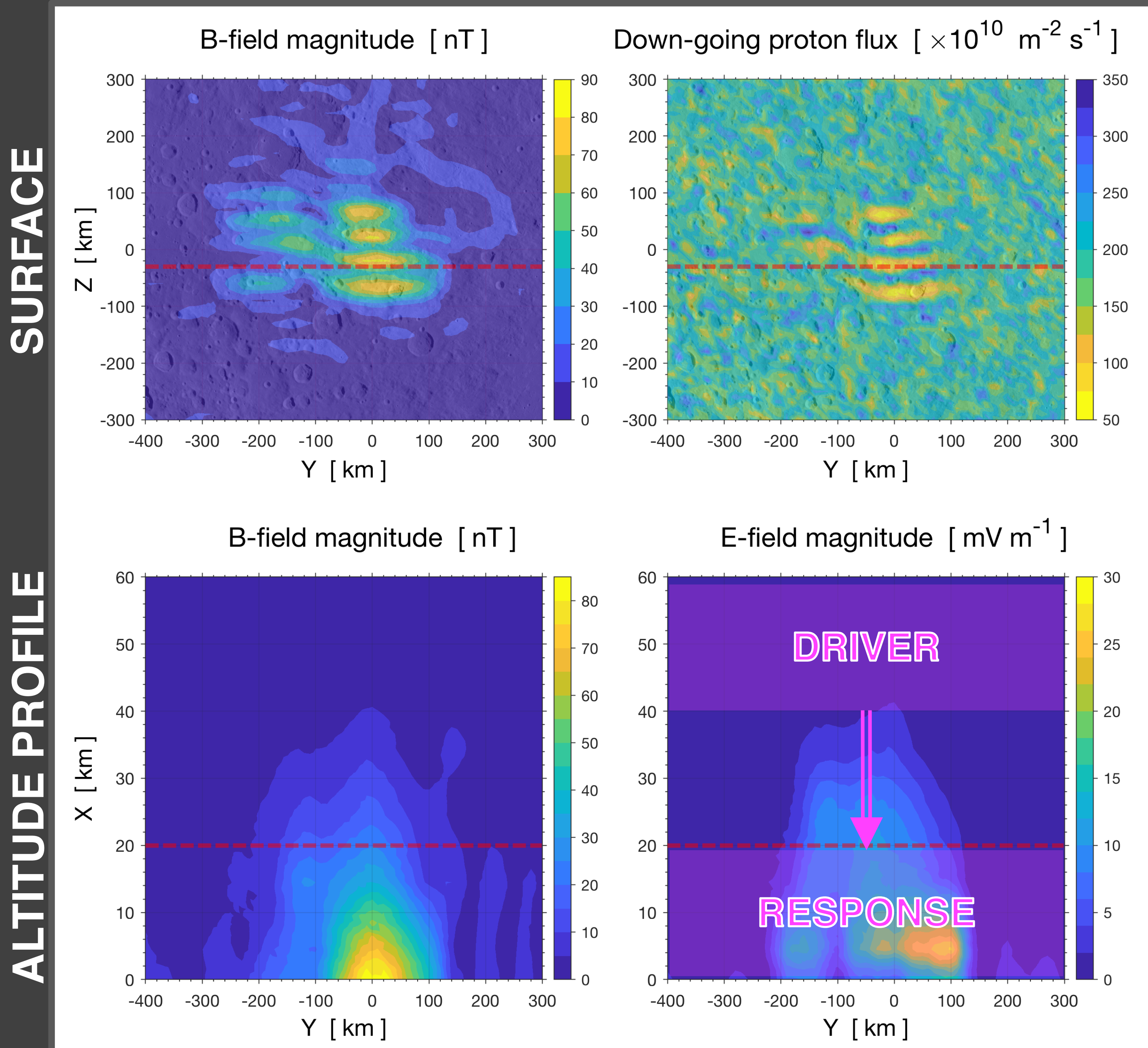
BOLAS Science – 3D Hybrid Simulation of Gerasimovich

SURFACE



10 km resolution at the surface captures the modulation of solar wind proton flux within crustal field region

BOLAS Science – 3D Hybrid Simulation of Gerasimovich



10 km resolution at the surface captures the modulation of solar wind proton flux within crustal field region

Altitudes < 20 km required to observe processes responsible for decelerating, deflecting and reflecting solar wind protons

Vertically-aligned, dual-point measurements required to determine cause and effect

BOLAS Instrumentation

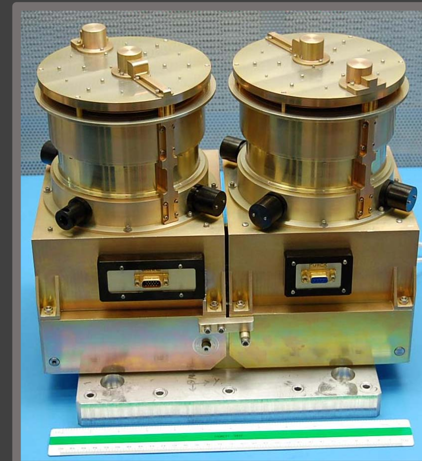
Primary Payload

Ion Spectrometer (Univ. of Iowa)
Incident and reflected proton energies and fluxes

Energetic Neutral Atom (ENA) Imager (GSFC)
Backscattered neutral hydrogen (and ambient electrons)

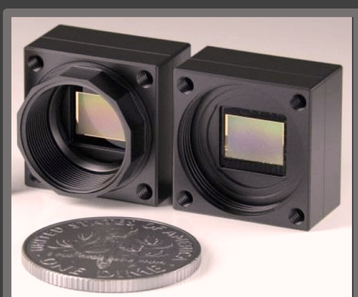
Mini-magnetometer (GSFC)
Ambient magnetic fields

Plasma Wave System (GSFC)
Electron densities, electric fields and dust impacts



Secondary Payload

Miniaturized Cameras
Tether diagnostics & surface imaging.



BOLAS – Frozen Science Orbit

Low-altitude lunar orbits are made difficult by “mascons” – fuel mass required for station-keeping is typically prohibitive.

“Frozen” orbits are stable, elliptical orbits that can reach low altitudes (e.g., LRO) and do not require station-keeping.

Stable for > 1 year

- Observe annual cycles and occasional events; e.g., meteoroid streams and coronal mass ejections (CMEs)
- Full local time coverage of surface targets every 6 months

Frozen orbit discovered with 30^{o} inclination – equatorial – and mean altitude of 90 km

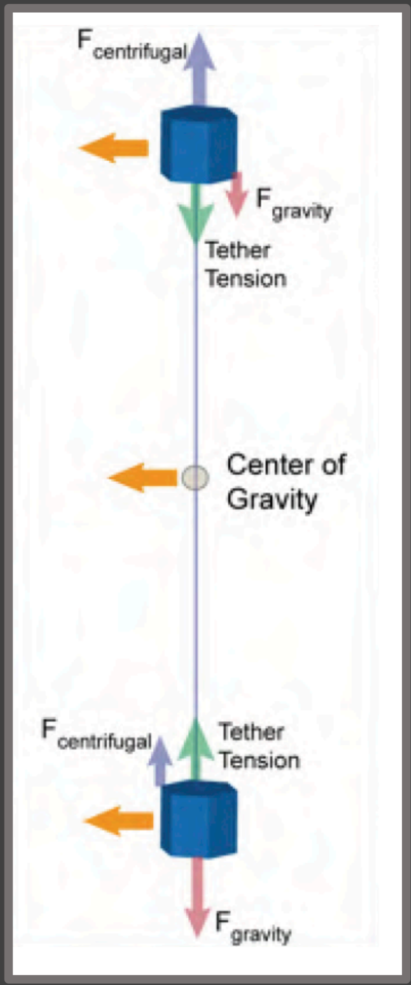
- Periapsis fixed around 30^{o} S
- Covers all strong crustal fields ($\gtrsim$ 300 nT at surface)
- Variable periapsis – minimum true altitude = 14.5 km

Periapsis at Gerasimovich – minimum true altitude = 23.8 km

Frozen orbit not low enough over Gerasimovich for science requirements (altitude $\lesssim$ 20 km)

BOLAS Tethered Microsat Dynamics

Gravity gradient aligns and stabilizes tethered formation



Collier et al. (2016)

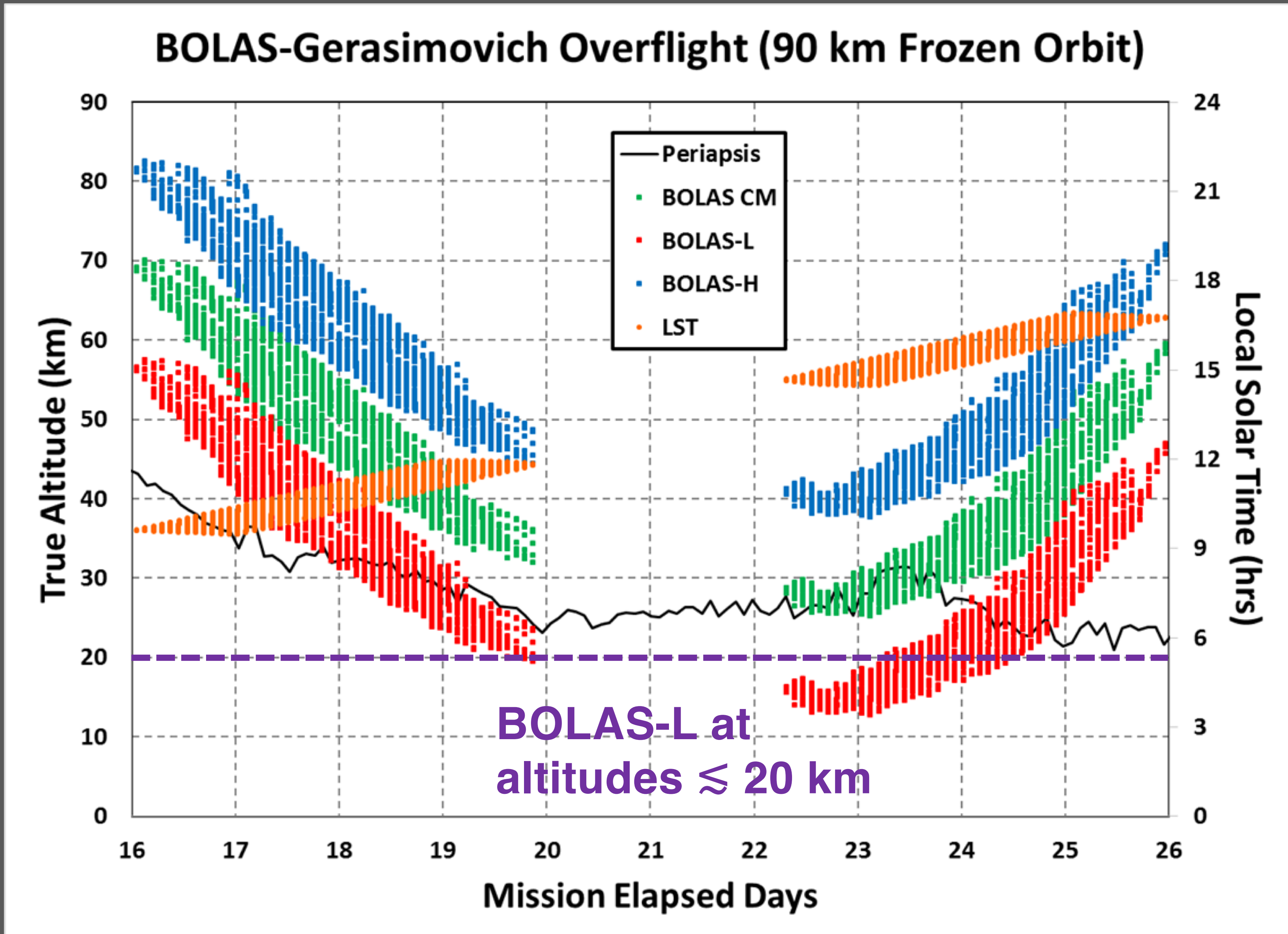
Tethered formation of two microsats enables lower spacecraft to obtain measurements closer to the Moon, while the center-of-mass of the formation follows the stable, frozen orbit.

BOLAS has 25 km-long tether, giving BOLAS-L

- **Periapsis true altitude = 2 km**
- **Gerasimovich periapsis true altitude = 11.3 km**

Addresses BOLAS science requirements for vertically-aligned, dual-point, low altitude ($\lesssim$ 20 km) measurements at Gerasimovich

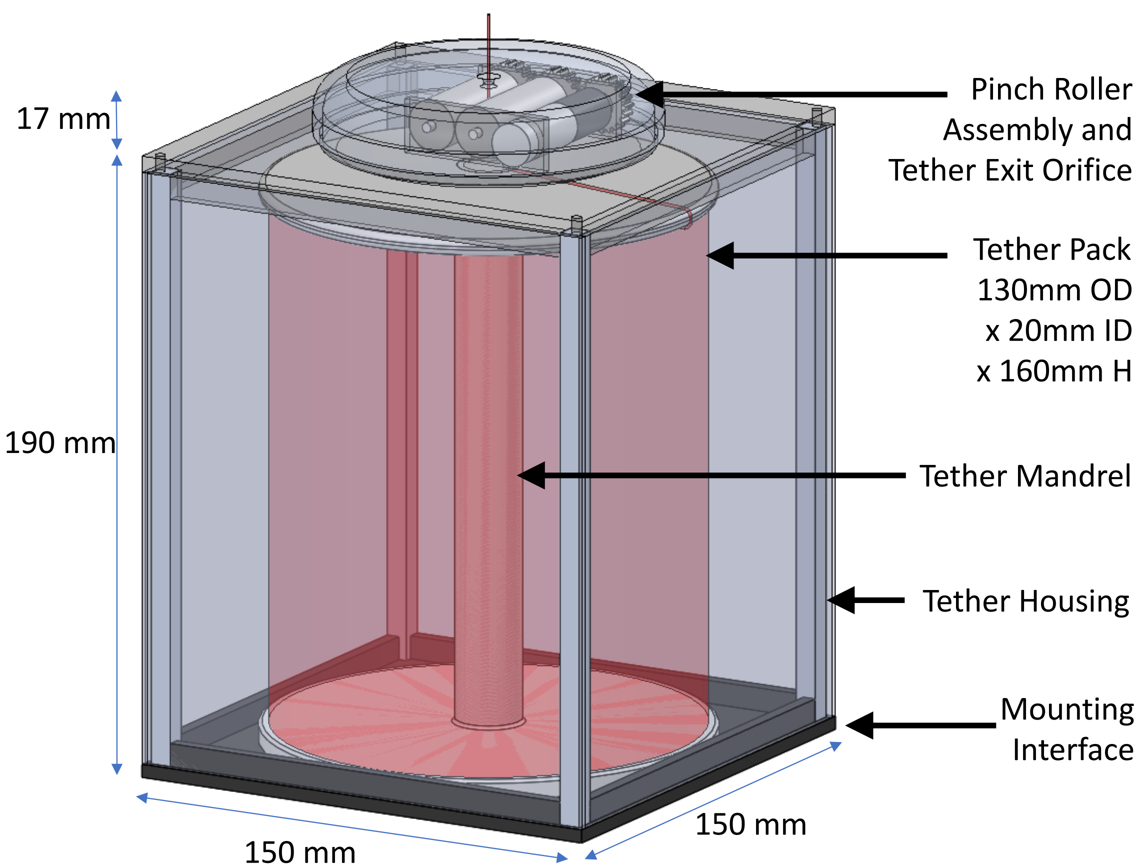
BOLAS – Tethered Frozen Science Orbit



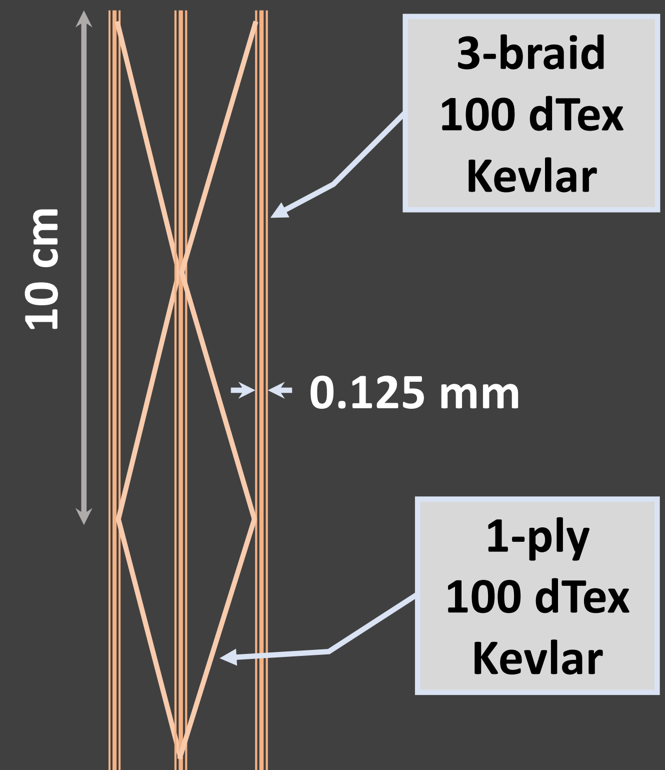
BOLAS – Tether and Deployer

Tether – Kevlar yarns braided into multi-line "Hoytether" structure to provide redundancy to survive meteoroid and exospheric dust impacts

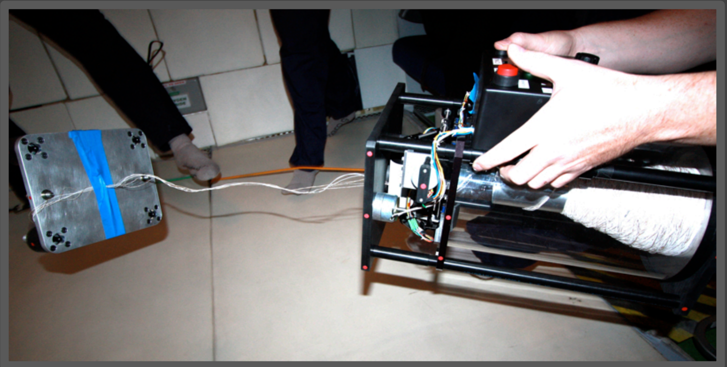
Tether Deployer System

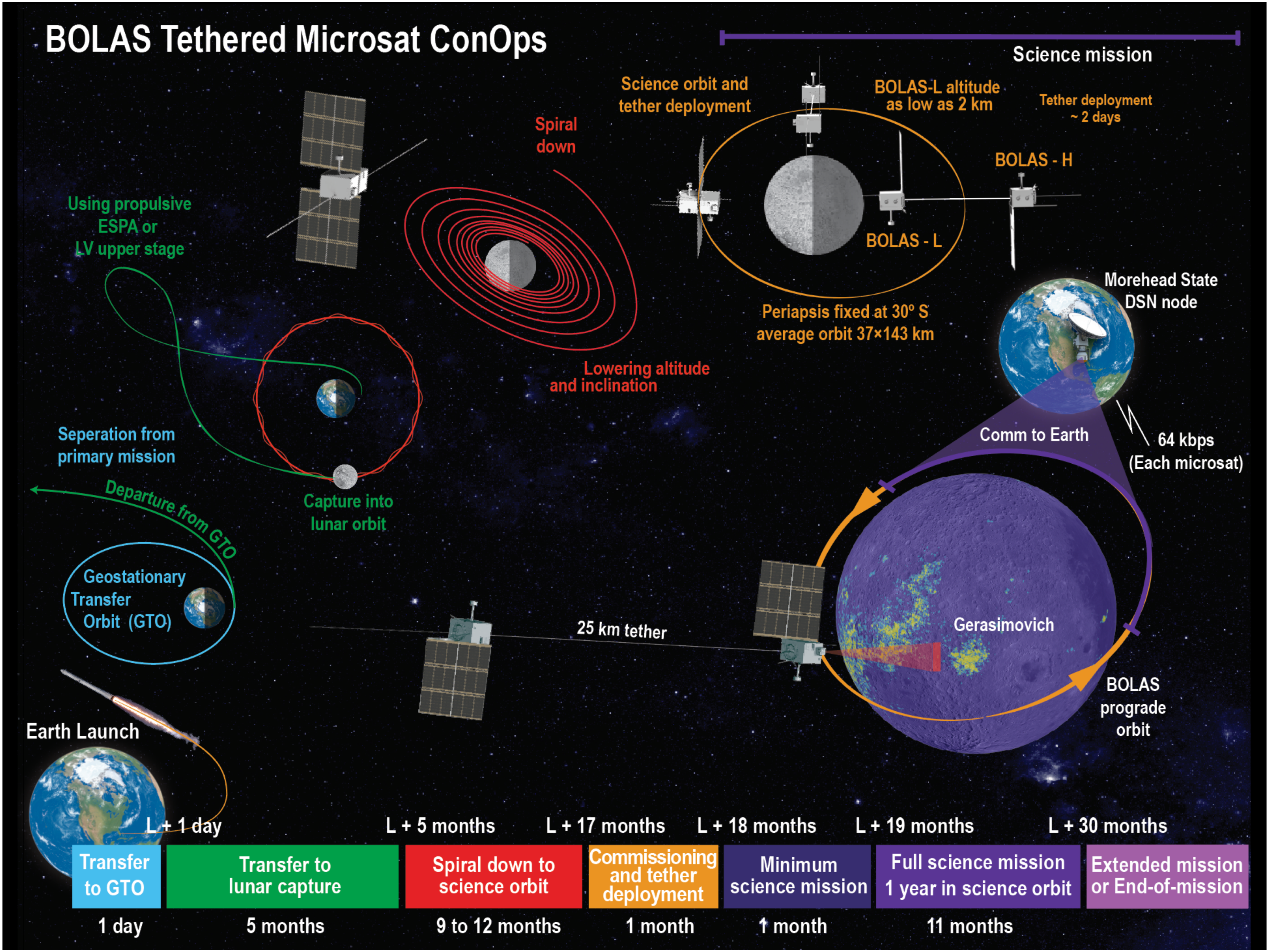


Tethers Unlimited, Inc.



Similar Deployer Tested in Microgravity for LOKI Program

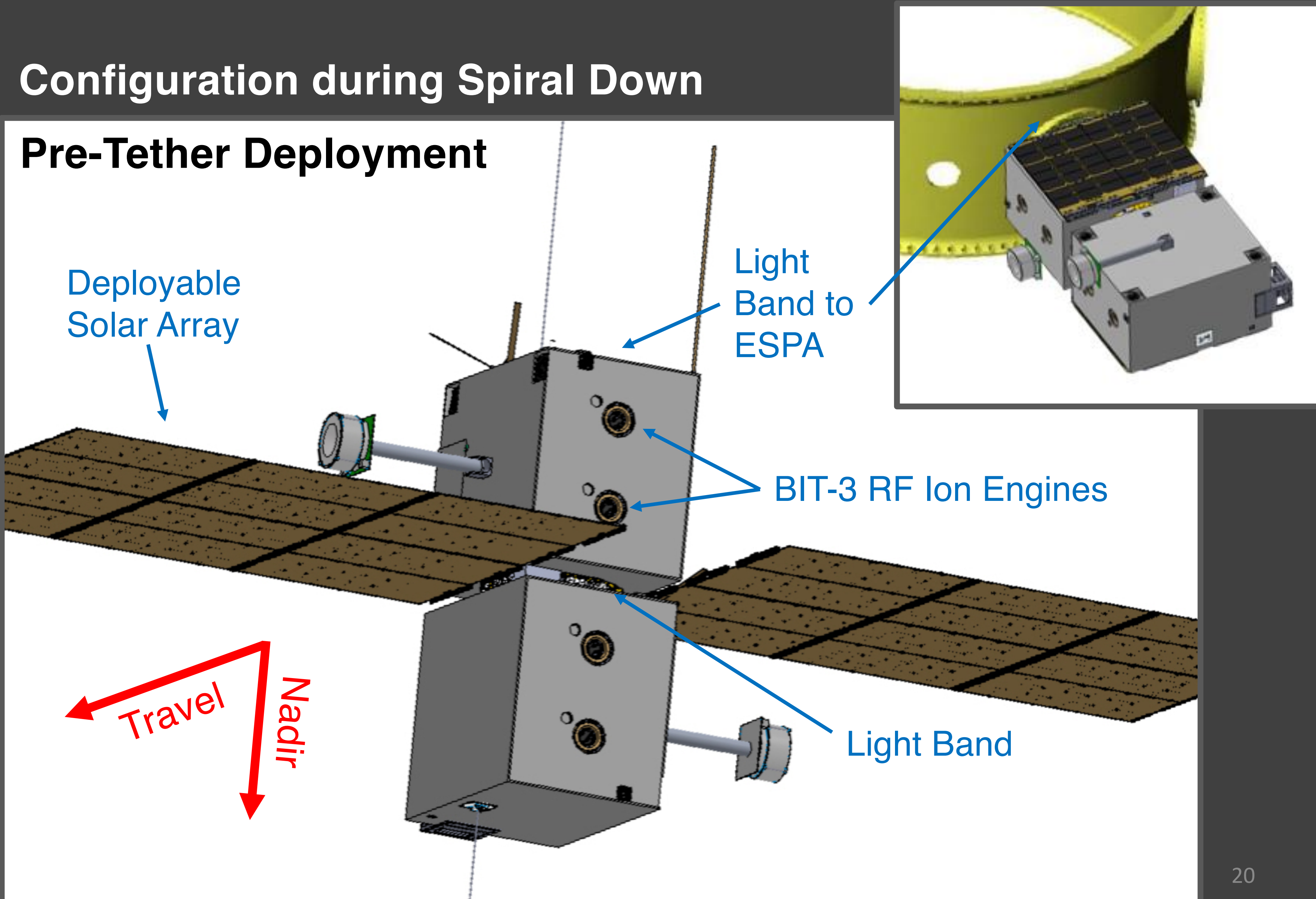




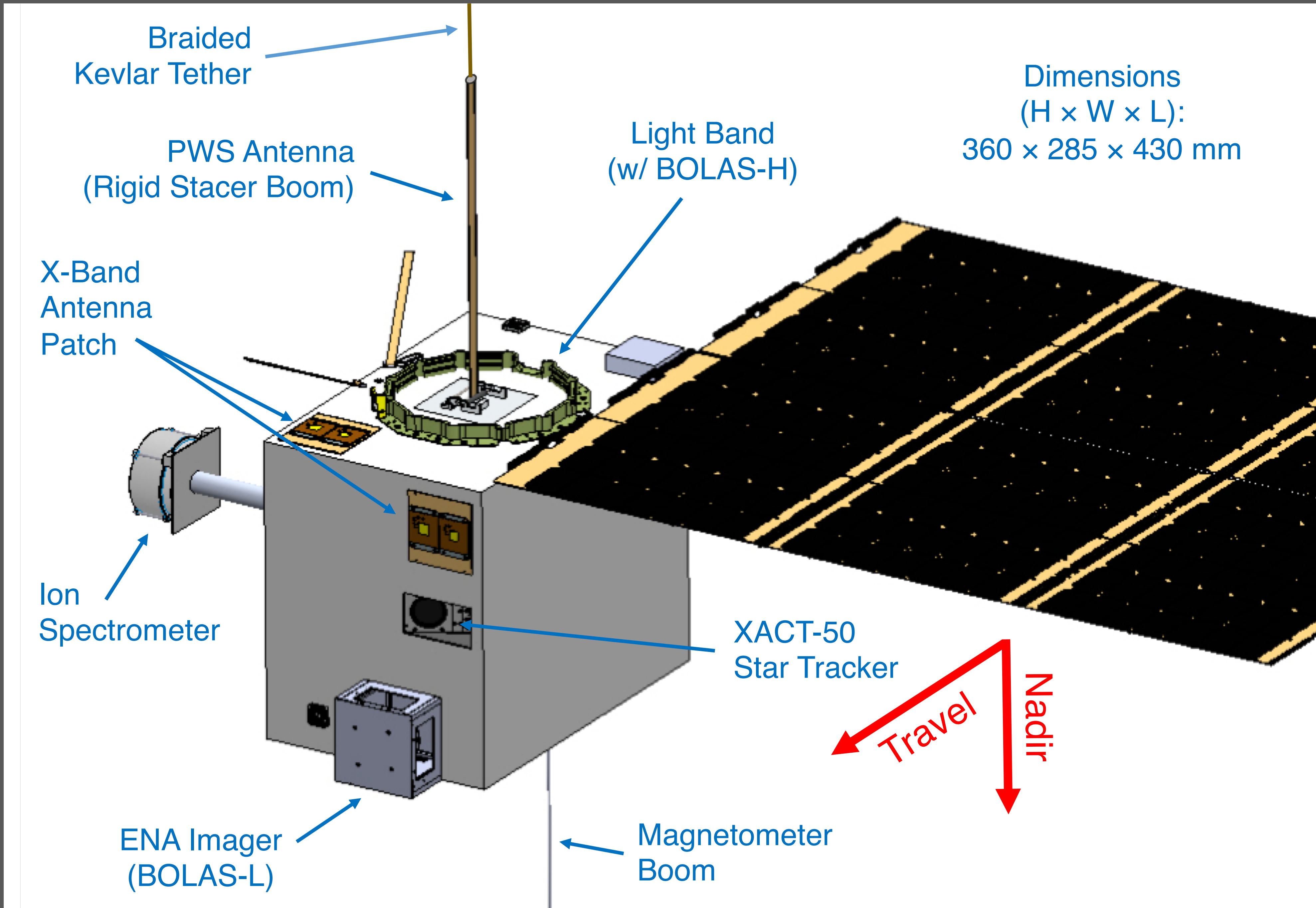
BOLAS Tethered Microsat ConOps
Science mission
Science orbit and tether deployment
BOLAS-L altitude as low as 2 km
Tether deployment ~ 2 days
Spiral down
BOLAS - H
BOLAS - L
Using propulsive ESPA or LV upper stage
Periapsis fixed at 30° S average orbit 37×143 km
Morehead State DSN node
Lowering altitude and inclination
Comm to Earth
64 kbps (Each microsat)
Seperation from primary mission
Departure from GTO
Capture into lunar orbit
Geostationary Transfer Orbit (GTO)
25 km tether
Gerasimovich
BOLAS prograde orbit
Earth Launch
L + 1 day
L + 5 months
L + 17 months
L + 18 months
L + 19 months
L + 30 months
Transfer to GTO
Transfer to lunar capture
Spiral down to science orbit
Commissioning and tether deployment
Minimum science mission
Full science mission 1 year in science orbit
Extended mission or End-of-mission
1 day
5 months
9 to 12 months
1 month
1 month
11 months

BOLAS Microsat Design

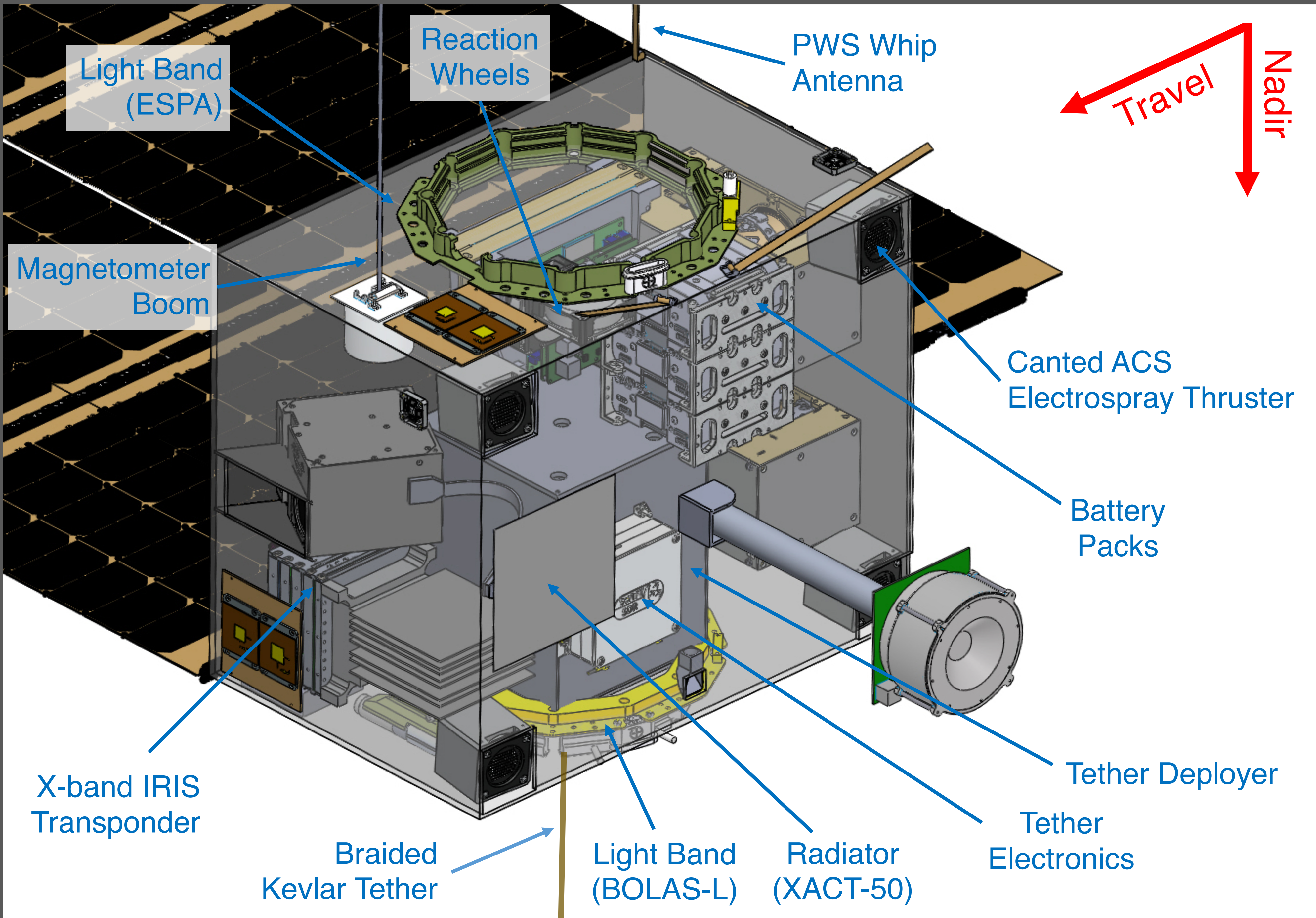
Configuration during Spiral Down



BOLAS-L – Post-Tether Deployment



BOLAS-H –Post-Tether Deployment



BOLAS Resources

Microsat	BOLAS-L	BOLAS-H
Mass [kg]	26.7	30.4
Peak power available [W]	240	240
Peak power required [W]	155	155
Telemetry available [kbps]	64	64
Telemetry required for primary science * [kbps]	39	39

* Assuming: 25% transponder duty cycle (~6 h per day)
10 / 90% split between burst and reduced modes

- Well within ESPA-class mass and volume limits
- Meets power and telemetry requirements
- Orbit-tether-instruments exceed science requirements

BOLAS Summary

- Compelling primary science goal to determine the role of solar wind in the evolution of the lunar surface
- Broad scope of “secondary” planetary science
- Highly relevant to NASA Science & Strategic Plans
- No “significant” technical hurdles
- Well within ESPA-class mass & volume limits
- Meets power, telemetry, thermal requirements
- Orbit-tether-instruments exceed science requirements
- Estimated costs within PSDS3 price range
- Game-changing use of tethered SmallSats enabling unprecedented low altitude observations